TOWARDS DIGITAL MICROFLUIDIC CIRCUITS: CREATING, TRANSPORTING, CUTTING AND MERGING LIQUID DROPLETS BY ELECTROWETTING-BASED ACTUATION

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ABSTRACT

This paper reports a breakthrough in our quest for digital microfluidic circuits — full completion of all four fundamental microfluidic operations: (1) creating, (2) transporting, (3) cutting, and (4) merging of liquid droplets, based on electrowetting-on-dielectric (EWOD) actuation. All the operations were achieved with 25 V_{DC}, lower than EWOD actuation voltages previously reported. We also report conditions to reduce the driving voltage even further and conditions to drive a droplet as fast as 250 mm/s.

INTRODUCTION

Recently much attention has been drawn to using surface tension for microfluidic actuation, because it becomes a dominant governing force on the microscale [1]. Compared with thermocapillary [2], the electrical control of surface tension is much more advantageous for microfluid actuations [3-8], because of its negligibly low power consumption. Among the known configurations, electrowetting on dielectric (EWOD) is considered prospective thanks to the electrochemical inertness of the surface, which allows for control of the wettability on a dielectric solid surface using electric potential. Pollack *et al.* [6] showed that an aqueous liquid droplet could be transported by EWOD. Lee *et al.* [7, 8] reported an addressable micro liquid handling technique by a general electrowetting as well as EWOD actuation, envisioning an eventual digital microfluidic circuits such as the one in Fig. 1. In this kind of liquid handling device, most fluidic operations can be carried out on a chip using discrete droplets rather than the usual continuous flow. Moreover, typical fluidic operations such as pumping and mixing can be performed by programmed electric signals rather than physical structures. This concept is very promising because the fabrication process is much simpler with no need to build moving micromechanical parts in the device.

For the fully functional digital microfluidic circuits that we proposed, four fundamental droplet manipulation mechanisms need to be first established: (1) creating, (2) transporting, (3) cutting, and (4) merging of droplets in the fluid path, as illustrated in Fig. 1. This paper reports the completion of all four such operations, based on electrowetting-on-dielectric (EWOD). All four operations were achieved with 25 V_{DC}, much lower than previously reported [7, 8]. Although droplet transportation has been demonstrated [6], droplet creation from reservoir by EWOD has never been reported, not to mention achieving all four operations on one chip. Droplet creation from a reservoir, the most difficult among the four, is critical for the success of eventual microfluidic circuits as it is analogous to A/D converter in electronic circuits. In addition, we report experimental verifications for the criteria of cutting a droplet, which we previously proposed [9]. We further develop a theoretical guideline to lower EWOD actuation voltage and experimentally confirm the argument by succeeding to actuate at 15 V_{DC}, the lowest ever reported. On the other hand, we also report a droplet speed as fast as 250 mm/s when over 100 V is applied in AC form.

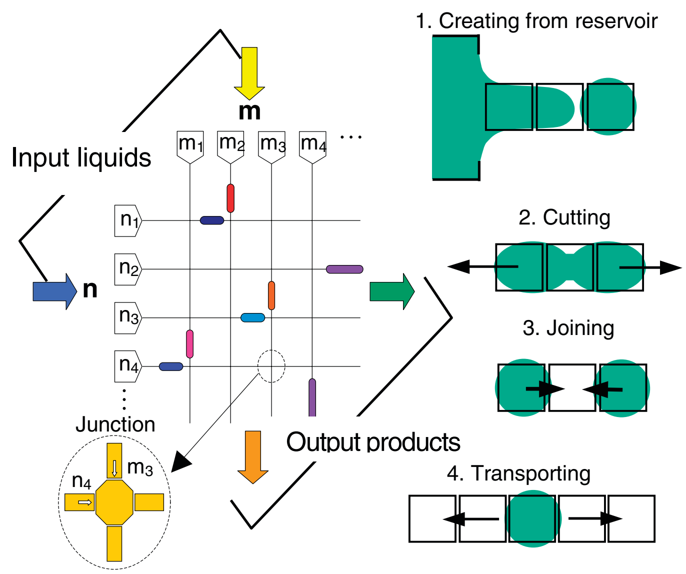


Fig. 1 Envisioned digital microfluidic circuit and the four fundamental droplet operations necessary

LOWERING ACTUATION VOLTAGE

A liquid droplet is placed in the gap space between the glass substrate with addressable control electrodes and the cover glass with a blank ground electrode (Fig. 2). There is no sidewall defining the channel. The spacers are only to define the gap between the substrate and glass cover. Liquid droplets are actuated by energizing control electrodes sequentially. As illustrated in Fig. 2, the asymmetry of radii of curvature at the two ends of droplet induced by asymmetric contact angles generates an internal pressure imbalance, resulting in liquid movements. Contact angle on the energized control electrode can be controlled by electric potential according to Lippman-Young's equation [10]:

$$\cos\theta(V) - \cos\theta_o = \frac{\varepsilon\varepsilon_o}{2\gamma_{LG}t}V^2, \quad (1)$$

where $\theta(V)$ is contact angle at electric potential V, θ_o contact angle with no potential, γ_{LG} the interfacial tension of liquid, ε_o the permittivity of vacuum, ε the dielectric constant and t the thickness of the dielectric layer.

A low voltage operation is desirable for driving liquids with conventional electric circuits. The fabrication of testing devices was focused on the selection of dielectric layers to reduce the driving voltage. For a given liquid, equation (1) implies that the electric potential required to generate a certain degree of wettability change can be reduced by using a thin dielectric layer or a high dielectric-constant layer. Following the above indication, we made the dielectric layer as thin as possible. A layer of 1000 Å silicon dioxide and 200 Å Teflon® gave us reliable EWOD actuations with as low as 25 V_{DC}. All the four fundamental fluidic operations in the next section were accomplished under this double layer condition. Thinner layers, however, are susceptible to electrolysis. When a very high dielectric-constant material such as Barium Strontium Titanate (BST, dielectric constant: 200-300) was deposited by MOCVD, we were able to reduce the operation voltage down to 15 V_{DC}. For more details, refer to Moon *et al* [11].

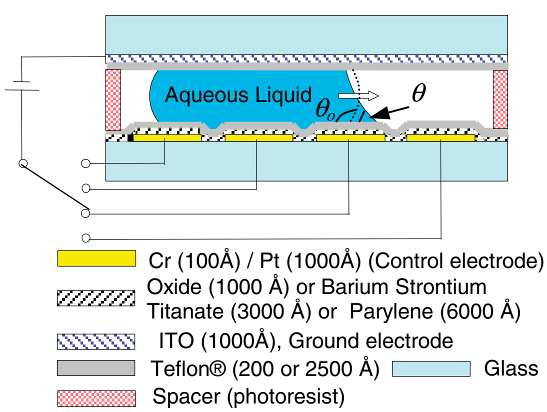


Fig. 2 Cross-section of fabricated devices. Dotted line indicates the initial shape of meniscus.

For the driving electrode, 100 Å chromium and 700 Å platinum were deposited and patterned by wet etching. The electrode is 1.0 mm × 1.0 mm in area. The inter-digitated fingers were placed between the electrodes to facilitate continuous movement of droplets between adjacent electrodes [6]. For the first dielectric layer, 1000 Å LTO was used for 25 V_{DC} operations, 3000 Å BST for 15 V_{DC} operations and 6000 Å Parylene for operations with over 100 V_{AC}. To make the surface on the top of the dielectric layer hydrophobic, 200 or 2500 Å Teflon® layer was spin-coated. The total capacitance is the serial combination of two dielectric layers. In order to control the channel gap size between the substrate and cover glass, a thick photoresist was used for the spacer. Channels of 70, 150 and 300 µm gap size were prepared and tested. The cover glass is coated with a transparent and conductive ITO (Indium Tin Oxide, < 15 Ω/square) as the ground electrode prior to being spin-coated with 200 Å Teflon®. The applied potential was adjusted by a power supply and the driving signals were switched by computer program.

CUTTING A DROPLET

For cutting a droplet, three control electrodes are used as shown in Fig. 3. The left and right electrodes are energized so contact angles on them reduce according to Eq. (1), resulting in an increase of the radii of curvature, r_2. In the mean time, the middle electrode is floated or grounded, inducing no contact angle change. As a result, the meniscus on the middle electrode contracts to keep the total volume of the droplet constant. That is, cutting is initiated with the elongation of the droplet in longitudinal direction and necking (negative R_1, shown in Fig. 3(a)) in the middle of the droplet.

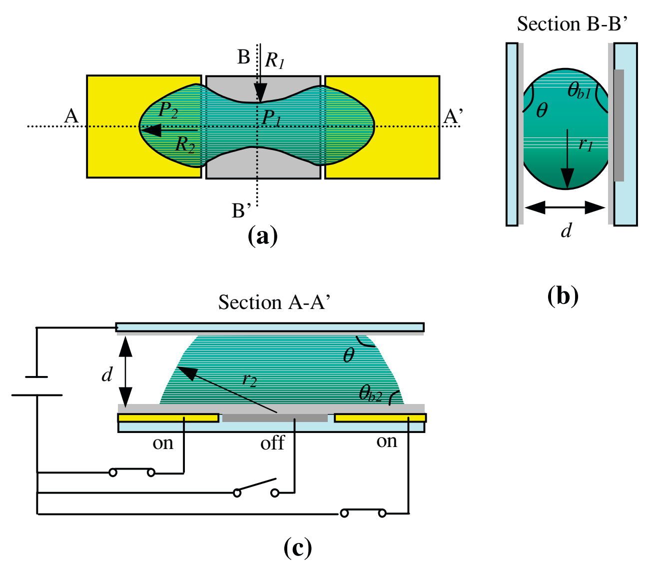
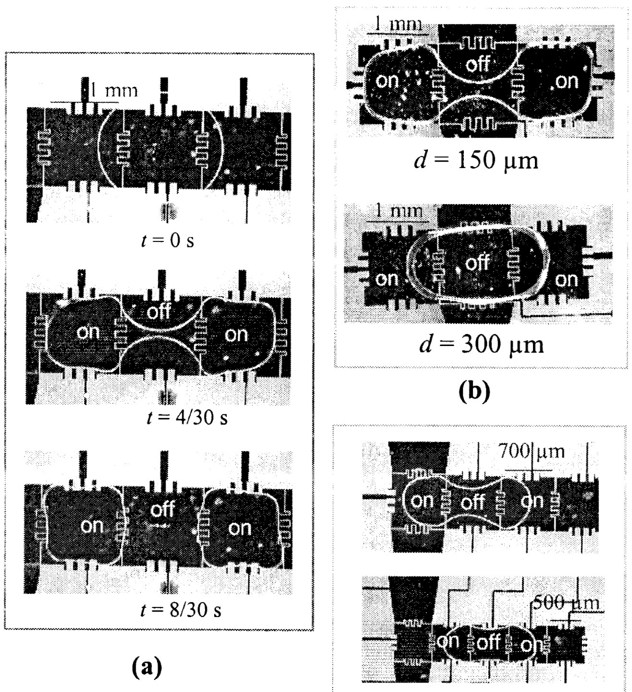


Fig. 3 Droplet configuration for cutting.

Using the force analysis in a squeezed droplet, we derived the criteria for cutting [9]:

$$\frac{1}{R_1} = \frac{1}{R_2} - \frac{\cos\theta_{b2} - \cos\theta_{b1}}{d}, \quad (2)$$

where R is the principal radius of curvature as shown in Fig. 3(a), r the principal radius of curvature as shown Figs. 3(b) and (c), and θ_b contact angle on the bottom wall. Subscript 1 indicates parameters in the middle region of the droplet and subscript 2 in the right or left end region of the droplet. Equation (2) implies that smaller channel gap and/or larger droplet (i.e., larger electrode) can induce necking (negative curvature) in the middle of the droplet and eventually make cutting of droplets easier. Since there exists a saturation in contact angle change by EWOD ($\cos\theta_{b2} - \cos\theta_{b1}$) [10-13], one may not be able to obtain any necking under even a very high electric potential. The geometry such as channel gap and/or electrode size needs to be designed according to a certain criteria such as Eq. (2).



(a)

(c)

Fig. 4 Cutting a droplet and verification of the criteria at 25 V_{DC}: **(a)** cutting a droplet (gap size d = 70 μm, electrode size = 1mm) **(b)** channel gap size effect (in both cases, electrode size = 1 mm) **(c)** electrode size effect (channel gap size fixed at d = 70 μm)

Experimental verifications of the above criteria were made. Figure 4(a) shows a successful cutting process with 70 μm channel gap, 1×1 mm^2 electrodes and 25 V_{DC} applied voltage. However, when channel gap is increased to 150 μm, a droplet necks but cannot complete cutting (Fig. 4(b) top). When the gap is increased further to 300 μm, EWOD actuation is too weak to even form a neck (Fig. 4(b) bottom). The analysis also predicts cutting becomes difficult as the electrode becomes smaller (Fig. 4(c)). Note that the extent of the necking decreases as the droplet size (electrode size) becomes smaller from 700 μm (Fig. 4(c) top) to 500 μm (Fig. 4(c) bottom).

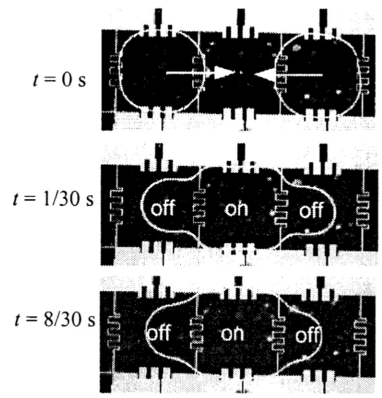


Fig. 5 Sequential pictures for merging two droplets

MERGING DROPLETS

Merging droplets is essential for mixing. Figure 5 shows merging was achieved by moving two droplets towards each other. The merging process, although opposite to cutting, does not follow the reverse procedure of cutting (Fig. 4(a)). Note that merging process does not involve any necking.

CREATING DROPLETS

To generate droplets, liquid needs to be first pulled out of a reservoir and separated from it. This process is associated with cutting but more difficult because electrowetting is not effective inside the reservoir. There exists only a weak force holding the liquid back, i.e., weak reaction force against the force pulling the liquid out. When the front meniscus is pulled out of the reservoir by EWOD, the liquid continues to follow the leading meniscus and then forms a long liquid column. The cutting point depends on the initial shape of the meniscus in the reservoir, on surface condition, and on how the control electrodes are activated. In fact, in order to pull a liquid column out of a reservoir

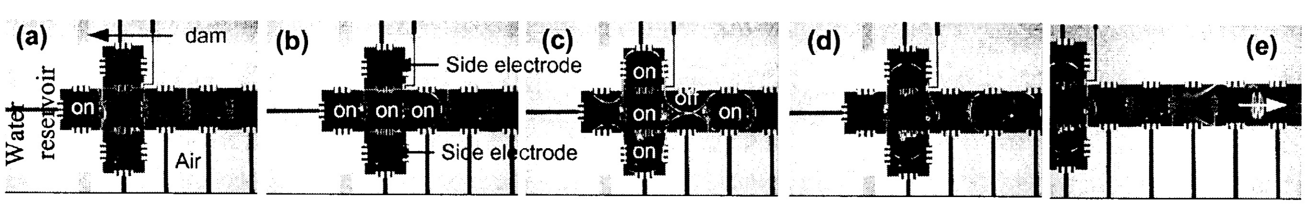


Fig. 6 Sequential images for creating a droplet from reservoir

on the initial shape of the meniscus in the reservoir, on surface condition, and on how the control electrodes are activated. In fact, in order to pull a liquid column out of a reservoir drop of 1-3 µl and generate a small droplet, 5-7 control electrodes were used. The minimum number of electrodes necessary to generate droplets from reservoir was rather unpredictable. This problem was overcome by placing two side electrodes beside the main fluid path (Fig. 6). By actively pulling the liquid normal to the main fluid path, the liquid can be virtually pulled back, enhancing the necking. This method makes creation of droplets more consistent and has two more main advantages: (1) reservoir can be either connected to a continuous source of flow or completely filled with liquid because it is not necessary to pull back with EWOD actuation, (2) controllable cutting position by changing the position of side electrodes. Furthermore, if the whole surface of the reservoir is covered with a hydrophobic layer, all liquid can be taken out by EWOD with no dead volume remaining in the reservoir.

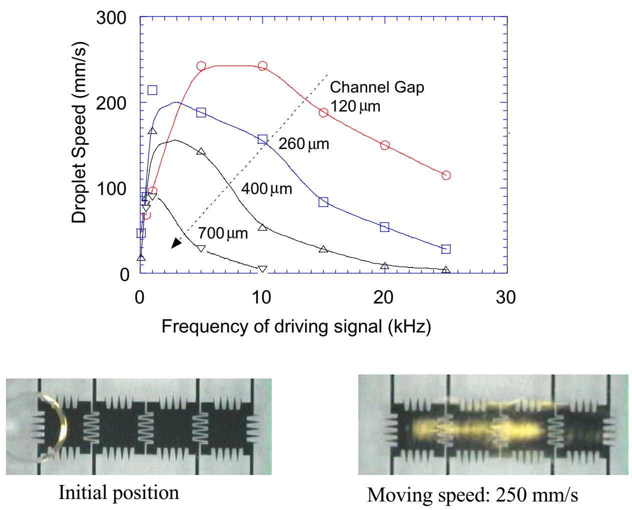


Fig. 7 Testing transporting speed with various channel gaps and frequencies of AC 150 V.

FAST TRANSPORTATION OF DROPLETS

Fast transportation of droplets is desirable for short process time on lab-on-chips. Higher electrical potential would generate higher contact angle changes and faster droplet movement. However, high electrical potential is prone to electrolysis. Dielectric layer used in this experiment was 2500 Å Teflon and 6000 Å parylene. Using DC voltage, the maximum speed was 30 mm/s. With AC potential, however, droplets can be transported as fast as 250 mm/s, one order of magnitude faster than the previous report [6]. Figure 7 shows the moving speed at various AC frequencies and gap sizes, and images of a moving liquid droplet.

CONCLUSIONS

Four fundamental microfluidic operations (creating, cutting, transporting, and merging of droplets) were accomplished using electrowetting-on-dielectric (EWOD) actuations, building for digital microfluidic circuits. All the fluidic operations were achieved at 25 V_{DC} applied potential, much lower than previously reported. A separate study showed that driving voltage can be reduced to as low as 15 V_{DC}, when a material of very high dielectric constant is used. Another study reveals conditions in which a liquid droplet can be driven as fast as 250 mm/s, one order of magnitude faster than the previous report.

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